

# Quantum Smart Matter

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## Abstract

The development of small-scale sensors and actuators enables the construction of “smart matter” in which physical properties of materials are controlled in a distributed manner. In this paper, we describe how quantum computers could provide an additional capability, programmable control over some quantum behaviors of such materials. This emphasizes the need for spatial coherence, in contrast to the more commonly discussed issue of temporal coherence for quantum computing. We also discuss some possible applications and engineering issues involved in exploiting this possibility.

*A condensed version of this paper will appear in the PhysComp96 conference proceedings.*

## 1 Introduction

Distributed control, using many sensors, computers and actuators, can improve the performance of systems at many scales. Examples include controlling traffic flow in cities [39], regulating office environments [33], active strengthening of structural materials [7], structural vibration control [31], reducing fluid turbulence [8] and adjusting optical responses [41]. The continuing development of micrometer-scale machines [11] and proposals for even smaller devices [22] constructed with atomically precise manipulations [4, 23, 34, 45] offer further possibilities for designing materials whose properties can be modified under program control, giving rise to so-called “smart matter” [35].

Smart matter is a material that locally adjusts its response to external inputs through programmed control. Such control is enabled by embedding sensing, computation and actuation ability within the material. Specifically, control programs are designed to use measurements of the system response to compute appropriate control inputs to the system, such as forces or electric fields, which are then imposed on the system by the actuators. This operation is known as feedback control because measurements of the system response are fed back to the controller for use in determining the control inputs.

To date, proposals for smart matter focus on controlling classical behaviors of materials [7, 35]. However, small, precisely constructed devices can also exploit quantum behaviors [1, 17, 43, 44]. Thus, an interesting open question is the extent to which the demonstrated abilities to modify quantum behaviors, together with distributed computation, can provide a much finer level of control of the properties of a material. This leads to *quantum smart matter*, which consists of actuators, sensors and computers integrated to operate on quantum behaviors.

In this context, classical control methods and computers have a limited role due to their use of a measurement process which necessarily disrupts the quantum behavior. Instead, control of the quantum behavior of materials is a possible application for quantum computers [5, 9, 18, 19, 20, 24, 37]. Although there has been some work on distributed, parallel quantum computers [40], the use of quantum computers

for controlling materials contrasts with most studies of such computers, which focus on purely computational questions such as whether they can compute classically intractable functions. Quantum computers are distinguished by their ability to operate simultaneously on superpositions of many classical states (“quantum parallelism”), and their restriction to unitary linear operations on such superpositions which can be used to produce interference among different computational paths. In particular, this restricts the programs to be reversible, and hence requires development of reversible devices [42].

In this paper, we discuss coupling the programability of quantum computers to properties of materials, to create quantum smart matter. Both classical and quantum smart matter share the basic idea of using a large number of integrated sensors, computers and actuators. They differ in that using quantum computers avoids the need to perform measurements on the quantum system. In the remainder of this paper, we first describe some of the control options for smart matter, then present an idealized example, and discuss a number of possible applications.

## 2 Types of Control

### 2.1 Global and Distributed Controls

A large majority of the control applications implemented today use global controls [10, 21, 49, 50]. These controllers employ a single centralized controller that receives measurements of the system’s state and delivers control inputs. Their popularity stems from their conceptual simplicity: the control program deals directly with the desired overall properties of the system and need not coordinate its activities with other controllers. More formally, existing theoretical tools provide a basis for establishing provable performance bounds and the optimal use of control resources.

Global controllers have serious drawbacks in the context of smart matter. First, manufacturing defects and variations in the environment make it difficult to accurately model the exact dynamic behavior of the system. Second, coordinating the activities of all the actuators in real time becomes an intractable designing and programming task as the number of active elements (sensors and actuators) increases. There can also be communication bottlenecks from the need to provide all the system measurements to the central controller in a timely manner. Finally, the failure of the single central controller completely eliminates all control of the system.

These difficulties motivate the use of distributed, or decentralized, control mechanisms. These control methods consist of a combination of many controllers, each designed and operated with limited knowledge of the complete system. This approach can allow control to be applied to more complex systems, including distributed computation [32]. While global performance cannot necessarily be guaranteed as with global controllers, decentralized controllers can, in practice, be remarkably robust to the failure of individual active elements, and are found in a variety of systems such as biological ecosystems, market economies and the scientific community. Some applications of distributed control include regulating office environments [33], traffic flow [39], and, in the context of smart matter, structural vibrations [31].

### 2.2 How Control Can Make Smart Matter

Materials with desirable properties can be created in a number of ways. For most materials in use today, the properties are built in through a suitable choice of component materials and fabrication method (e.g., plastics and metal alloys). This technique is very robust when suitable materials can be found, but limited by properties of natural materials the available fabrication technologies. In effect, this procedure designs the system so additional control is not needed, i.e., the uncontrolled behavior of the system has the desired properties already. Unfortunately, once fabricated it is difficult to change the material

properties. This is especially true of changes that should take place only at specific locations and occur rapidly in response to some environmental change.

One way to change the properties of materials in a controlled manner is through the use of external fields applied to the whole system. Provided the relevant physical properties change in response to this field, changing the field provides a global control of the material. Examples include piezoelectric crystals where electric fields modify mechanical properties and the use of lasers to modify chemical reactions of large groups of molecules [13, 16, 27, 51]. If the system can be accurately modelled these external fields can be designed a priori. However, designing effective global control for large, dynamic, heterogeneous systems is intractable due to the scale and difficulty of modelling their quantum behavior. Alternatively, if many repeated experiments are feasible, the controls can be adapted to the system by incremental changes that improve performance based on measurements of the system response.

Another approach is to apply the required fields locally through embedded actuators, but still without any sensors. This alternative can handle spatial variations in the material that are known in advance, or provide a match to a fixed system through overall adaptation after many trials. This alternative still does not dynamically adjust to variations resulting from imperfections in the system.

The above control methods work without any feedback, either by having good knowledge of the system behavior so the control force can be suitably designed, or through an adaptive process where different controls can be applied to many copies of the system to determine which method is best. When these conditions do not hold, these control methods are not effective.

Smart matter, where sensors and actuators are integrated in large numbers throughout the material, leads to an alternate control method: the ability to sense and act independently on a local scale is employed to create desirable global behavior. This approach allows the control force to respond dynamically to unanticipated changes in the system or compensate for an inaccurate model of the dynamics at a very local scale. In effect, this allows the adaptation to take place while the system operates and in response to local variations, in contrast to a global adaptation of controls without local sensors where adjustments are based on the average behavior of many trials or copies of the system. A good example of the need for dynamic control is the behavior of vortices near a surface moving through a turbulent fluid. Here local sensors can allow response to individual vortices, whose location and occurrence are not readily predicted.

The most extreme case of smart matter is when the computation needed for the control is fast compared to any relevant changes in the physical configuration of the material. This allows for a decoupling of the slow physical degrees of freedom, which we denote by  $P$ , from the rapid computational degrees of freedom, denoted by  $C$ , in the same way that molecular or solid-state dynamics can often be approximated by considering separately the behavior of the electrons and the atomic nuclei. For example, this could be achieved by using light particles for the computation while heavy ones determine the relevant physical response. Viewed another way, within a given implementation, this requirement also limits the number of computational steps that the control program can perform to determine its result, thus, defining the maximum acceptable latency of the control system.

Finally, the distinction between a variety of individually fabricated materials and smart matter, where properties can be changed under program control, is somewhat analogous to the distinction between customized electronic circuits for specific tasks and the use of general microprocessors. In the former cases, the customized material or circuit have a fixed set of properties, and can be well-matched to specific applications whose requirements do not change rapidly. For the latter, the programmability of smart matter or microprocessors, allows for a wider range of applications and flexible response to changes.

## 2.3 Controls for Quantum Smart Matter

Controlling quantum behaviors elegantly extends the capabilities of smart materials, since the active elements can operate with the full quantum state of the material. Realizing this possibility requires translating classically based control methods to quantum systems. These methods include controlled behavior based on either feedback or modelling [10, 21, 49, 50]. The difficulty of applying these control techniques will depend on the way the system is constructed.

At one extreme, precise construction [22] simplifies the control problem by allowing accurate modelling of the environment of each device and individually tailored programs, but imposes severe difficulties for fabrication. On the other hand, more readily manufactured devices will exist in a statistically variable environment, making the control design more difficult. It is this latter case that we mainly focus on here, as it raises a number of engineering control issues where sophisticated controls can compensate for current inability to precisely fabricate materials.

One consequence of employing localized control is that creating macroscopic effects with microscopic controllers will require a large number of controllers. An immediate consequence is the requirement that these controllers be relatively homogeneous in design and function to simplify their design and construction. Furthermore, each controller will be required to act either autonomously, or in concert with only a few others, since the design of complex interactions among so many controllers using a global model and algorithm is intractable. Thus, quantum smart matter will be based on controllers, designed with local knowledge and behavior, which are homogeneous and act autonomously to achieve a desired macroscopic effect.

A second consequence is that global simulation and performance predictions will be statistical in nature due to the inability to precisely specify each controller's detailed environment, or perform simulation and optimization for so many degrees of freedom. In fact, the precise location of the devices would be described according to a probability distribution rather than known a priori, as assumed by standard control methods. This fact will require different types of systems analysis than are typically employed with classical systems.

In a control context, the forces acting on the physical degrees of freedom of a material must also depend on the computational ones. This observation is the analog of actuators in classically defined smart matter where results of a computation can change the forces acting on the physical system. Thus, the potential acting on  $P$  must be a function  $V(P, C)$ . Within the range of variation of this function, the control program can adjust  $C$ , based on the value of  $P$ , to produce an effective physical potential defined by

$$V_{\text{eff}}(P) = V(P, C(P)) \quad (1)$$

Because a quantum computer can perform this operation on quantum superpositions, it produces a system whose relevant physical behavior is governed by  $V_{\text{eff}}(P)$ , a controlled potential for the quantum system.

This discussion illustrates the difference between quantum smart matter, controlled by quantum computers, and smart matter whose control is determined by a classical computer. Since quantum computers operate on superpositions they are essentially applying all possible control actions weighted by the wave function values. Hence, quantum smart matter does not need to measure quantum states for feedback. By contrast, classical computers can't give feedback control since they would require a measurement of the state, hence collapsing the wave function.

Eq. (1) also illustrates a similarity between quantum and classical control of smart matter: both types of control modify the potential governing the system's dynamics. Quantum smart matter does this for quantum systems, without collapsing the wave function, while classical feedback modifies classical dynamic system properties.

Another important control issue is that of stability: whether the control achieves the desired behavior while maintaining the state of the system near some equilibrium configuration. Quantitative criteria for stability are given by results from control theory [50]. For the case where the control force does not depend explicitly on time, stability amounts to a bound on the total energy of the system. More specifically, for reversible, non-dissipative, quantum systems stability implies that the total energy of the system is constant in the absence of external inputs.

These results can apply much more generally, e.g., when the control force has an explicit time dependence, through the use of Lyapunov functions [50]. A Lyapunov function  $\Lambda(P, t)$  is a function of the system state, including the time dependence introduced by adjustments made by the control program. It may also have an explicit time dependence. If  $\Lambda$  is a convex function of  $P$  within some region including the initial state of the system,  $\Lambda$  has a non-positive total derivative with respect to time, and  $\Lambda(P_0) = 0$  at some point  $P_0$  within that region, then the entire system will be stable with control [50]. In essence this criterion determines when control feedback could positively amplify small perturbations in the system state, resulting in unstable behavior.

This result suggests a direct link between the potentials,  $V(P, C)$ , and classical control theory in which there are several synthesis methods that guarantee stability and performance of the controlled system. Such synthesis techniques would be employed to design the control program computing values for  $C$  such that it is reversible and satisfies the stability conditions for  $V_{\text{eff}}$ . Thus, controlled stability could be guaranteed for individual systems. However, stability of each individual system does *not* guarantee stability of the entire macroscopic system, unless each system is entirely autonomous. As an example, instability could arise when a small change in one part of the system gives rise to larger changes in other parts. Furthermore, the theory for control stability developed for classical systems will need to be extended to account for quantum systems where the long time behavior can be very different from the classical counterpart [29].

This discussion indicates that while design and synthesis of individual controllers may be put into a form that guarantees some measure of local stability and performance, global stability is not as straightforward a problem. Such global stability measures would likely differ from those of standard control theory in being a statistical expectation of stability, rather than a specific proof. Stability in this sense is particularly desirable under the assumption that the undesirable interaction of enough elements could reduce the expectation of stability for the entire system, and introduce undesirable behavior. Hence, the interactions present at the microscopic scale to which control is being applied would have to be determined, estimated, or implicitly considered because the application of localized controllers to achieve global results is inherently affected by the strength of (potentially) unmodelled interactions.

### 3 Programmable Quantum Behavior

Consider a one-dimensional system with a single extra binary degree of freedom. In this case the physical degree of freedom is the position, i.e.,  $P = x$ , and the computational degree of freedom  $C$  is 0 or 1. A simple potential would be to have two distinct functional forms  $V(x, 0)$  and  $V(x, 1)$ , as shown in Fig. 1. Suppose the system is initially prepared in the state  $|\psi\rangle = \sum \psi(x)|x, 0\rangle$  and then acted on by a quantum computer whose program sets  $C$  to 0 or 1 depending on whether  $x \leq 0$  or  $x > 0$ , respectively. This gives

$$|\psi\rangle = \sum_{x \leq 0} \psi(x)|x, 0\rangle + \sum_{x > 0} \psi(x)|x, 1\rangle \quad (2)$$

As this state evolves, amplitudes from positive and negative values of  $x$  become mixed and the control computation acts to readjust  $C$ . Provided this computation is fast compared to the physical evolution,

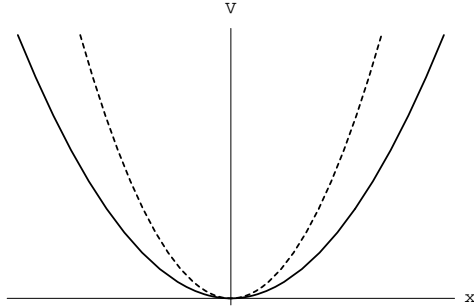


Figure 1: Example potentials  $V(x, C)$  for use with quantum smart matter. Two cases,  $V(x, 0)$  and  $V(x, 1)$ , are shown by the solid and dashed curves respectively, corresponding to a system with two computational states.

this gives in effect the behavior governed by the programmed potential. Other effective potentials could be constructed with different programs to compute  $C$  from  $P$ .

In this example, the result is an asymmetric potential as has been studied in the context of second harmonic generation in optics [44]. This illustrates the trade-off between smart materials and direct construction of materials with the desired effective potential. On the one hand, the properties of smart materials can be readily modified simply by changing the program in the control computers. On the other hand, direct implementation in materials allows for a faster response but becomes more difficult as more complex or time-variable potentials are considered.

As a final comment on this example, note that it made use of quantum parallelism but no use of interference. The latter capability of quantum computers is crucial for their possible improvement on classically intractable problems, and provides additional possibilities for designing behavior of smart matter. For instance, the use of destructive interference could be used to cancel the amplitudes of certain undesirable behaviors, a feature that is not possible with classical computations, even if they are probabilistic.

So far, we have described the behavior of a single quantum controller. For use in smart matter, we would have a system consisting of a large number of such devices to allow distributed control over specific quantum behaviors of the material. Results could include programs that provide different behaviors at different spatial locations, as well as changing with time. Furthermore, the control computation could make use of some of the computational states of its neighbors, providing a way to build correlations among different regions of the material. As an example of how simple programmed couplings can lead to more complex potentials suppose we start with two independent one-dimensional systems whose individual potentials take the form  $V(x, C)$  shown in Fig. 1. The overall system potential is then

$$V(x_1, C_1, x_2, C_2) = V(x_1, C_1) + V(x_2, C_2) \quad (3)$$

We can couple the behaviors together with a control program that, for instance, sets  $C_1$  to 0 or 1 depending on whether the *other* system state satisfies  $x_2 \leq 0$  or  $x_2 > 0$ , respectively, and vice versa for  $C_2$ .

In summary, quantum smart matter relies on potentials that can be adjusted by their dependence on degrees of freedom that can be rapidly changed under program control. To maintain superpositions, the control computations must rely on quantum computers. Finally, if the promise of quantum computing is realized, this capability could be used to create complex, varying potentials governing the behavior of matter.

## 4 Examples

If implemented, quantum smart matter provides the *capability* for using local control to produce desired behaviors. However, beyond the difficulty of fabricating such systems, there remains the challenge of *designing* suitable control algorithms.

### 4.1 Controlling a Single Harmonic Oscillator

To illustrate possible control methods, consider the behavior of a one-dimensional harmonic oscillator subjected to an additional control force so the effective potential is

$$V(x) = \frac{1}{2}\omega^2 x^2 + V_c(x, t) \quad (4)$$

For simplicity we restrict the control potential to be of the form  $V_c(x, t) = \frac{1}{2}kx^2 - f(t)x$ , with the corresponding control force given by  $F_c(x, t) = -kx + f(t)$ . The first term in this control potential is a time-independent force proportional to  $x$ , which just changes the basic frequency of the system to be  $\Omega = \sqrt{\omega^2 + k}$ . The second term gives a time-dependent control force that acts equally on the whole system, i.e., has no  $x$  dependence.

With these choices, the behavior of the wave function is readily determined [25], and is particularly simple for gaussian wave packets, i.e., wave functions of the form

$$\psi(x) = \frac{1}{\sqrt{\sqrt{2\pi}\sigma}} e^{-(x-p)^2/(4\sigma^2)} \quad (5)$$

where  $p = \langle x \rangle$  denotes the position of the center of the packet and  $\sigma = \sqrt{\langle x^2 \rangle - \langle x \rangle^2}$  characterizes its spread. As the system evolves from this initial state, the wave function continues to be described as a gaussian packet whose position, width and phase vary with time. In particular, the position of the center of the packet at time  $T$  is given by

$$p(T) = p(0) \cos(\Omega T) + \frac{1}{\Omega} \int_0^T f(t) \sin(\Omega(T-t)) dt \quad (6)$$

In this context, designing a control amounts to finding values of  $k$  and  $f(t)$  to achieve desired behaviors. The portion of the control force that does not depend on  $x$ , i.e.,  $f(t)$ , can be delivered either from an external global source or through the computations of the local controller. The forcing term  $f(t)$  can be determined this way because it does not involve any knowledge of the system state and hence does not require any sensor values. However, providing a force that does depend on  $x$ , in this case a modification of the oscillation frequency through the value of  $k$ , requires the applied force to depend on the system state. For a classical system this result would require the controller to measure the state for use in its control computations. Employing quantum computers for control of quantum systems, however, means that the controller acts on all possible states of the system, through quantum parallelism.

Often many choices of the control force will achieve the same objective. In these cases, additional criteria can be added to the design. A common additional criterion is to pick from among the feasible controls, i.e., those that produce the desired behavior, the one that minimizes some measure of the applied control force, e.g.,

$$\int_0^T \langle F_c(x, t)^2 \rangle dt \quad (7)$$

This constraint acts to reduce the control gain required, in the control design process, and therefore the actuation authority required. From a practical standpoint small gain controllers are desirable since any system noise encountered undergoes minimum amplification in the feedback control process.

For example, suppose we want the system's position, or more precisely the expected value of the position, to be at a desired value at a given time, i.e., we want  $p(T) = \hat{p}$  at a particular time  $T$ . This task is accomplished without sensors assuming accurate information about the system parameters and the dynamics can be integrated, as given in this case by Eq. (6). Under these conditions, sensors are not needed to determine how the system will behave and we can get the optimal behavior. With the explicit result of Eq. (6) and knowledge of the system parameters, in this case the frequency  $\omega$  and the initial position  $p(0)$ , we can obtain the desired control by choosing  $k$  and  $f(t)$  such that  $p(T) = \hat{p}$ . The choice that minimizes Eq. (7) can be determined with standard variational techniques [2] to be  $k = 0$  and

$$f(t) = \frac{4\omega^2 (\hat{p} - p(0) \cos(\omega T))}{2\omega T - \sin(2\omega T)} \sin(\omega(T - t)) \quad (8)$$

An example of the resulting behavior for  $p$  is shown in Fig. 2.

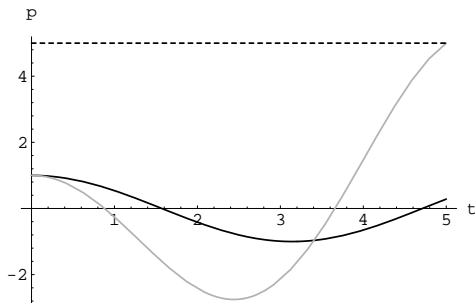


Figure 2: Expected position of a gaussian wave packet with (gray curve) and without (black curve) control. Here the parameters are  $\omega = 1$ ,  $\hat{p} = 5$ ,  $p(0) = 1$  and  $T = 5$ . The dashed line shows the desired final position of the packet  $\hat{p} = 5$ .

This example shows how a control without feedback can correctly produce desired behaviors provided the system is accurately modeled, and it can be solved to determine the dynamical behavior. More realistically, we may have information on the nominal characteristics of the material, but various imperfections in the fabrication process or environment will cause the actual system to vary from the ideal case. In addition, anharmonicities in the potential will make it very difficult to integrate the dynamics even if the exact system parameters were known. Thus, as described in §2.1, this control method will not work as well when applied to more realistic systems.

Feedback control using sensors can address these problems to some extent. For instance, suppose we are attempting to control to a specific path  $p(t)$ , such as the one shown in Fig. 2, to reached a desired value  $p(T) = \hat{p}$ , by using a force  $f_{\text{ideal}}(t)$  given in Eq. (8). If the system behavior were perfectly known, the actual system would follow this path, according to Eq. (6). Imperfections in the model or its evaluation will cause the system to deviate from this path. One way to address this is to add a feedback control force of the form  $-\alpha(x - p(t))$ . For the symmetric wave packets treated here, this additional force would have zero expected value if the system matched the modeled behavior. The overall control potential becomes

$$V_c(x, t) = \frac{1}{2}\alpha x^2 - (\alpha p(t) + f_{\text{ideal}}(t))x \quad (9)$$



Even if the system dynamics is only approximately known, a large value for  $\alpha$  will keep the system fairly close to the ideal path. On the other hand, this also means the controllers are using stronger forces, hence increasing the value of Eq. (7). This illustrates a general trade-off that feedback control provides: better performance when the system behavior is not known precisely, but at the expense of larger control forces. An example is shown in Fig. 3.

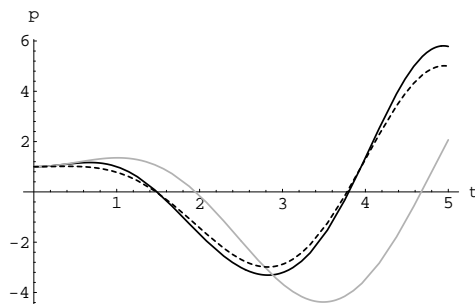


Figure 3: Using feedback to compensate for an imperfect system model. Expected position of a gaussian wave packet with (black curve) and without (gray curve) the addition of feedback control. The dashed curve is the ideal path that would have been followed without feedback if the system exactly matched the assumed model. The parameters are  $\omega = 1$ ,  $\hat{p} = 5$ ,  $p(0) = 1$  and  $T = 5$ . The control force is determined from the incorrect assumption that  $\omega = 1.5$  and feedback uses  $\alpha = 10$ .

## 4.2 Other Control Methods

In addition to providing more robust compensation in the presence of imperfect system models, feedback control (i.e., forces that depend on the value of  $x$ ) can be used to modify the shape of the potential which governs dynamic behavior. One example of using this ability is to manipulate the width of the wave packet, something not possible for a constant applied force. Furthermore, by changing the effective spring constant of the system, the control can change the energy level spacing, and thus the frequencies with which the system will resonate. Near resonance, a small change in  $\Omega$  can produce a large change in the system response. This result represents a case where small control forces can have a relatively large effect. Specifically, near resonance, the size of the system response to an external force of frequency  $w$  is proportional to  $1/(\Omega - w)$ . Thus, small changes in the value of  $k$  in the controller design, and the consequent small changes in  $\Omega$ , can lead to large changes in the system response. This change could in turn alter the damping of the external force, e.g., low frequency sound waves in the system. Provided these mechanical frequencies were small compared to the rate of the control computations, the control force would be able to track and respond to the external force at the desired frequency.

Another control task involves coupling the behavior of distinct parts of the smart matter. For example, suppose we have two oscillators whose behavior we want to have correlated. One way to do this is add a control force  $k(x_2 - x_1)$  to the first oscillator, and  $k(x_1 - x_2)$  to the second. This gives an overall effective potential of

$$V_{\text{eff}}(x_1, x_2) = \frac{1}{2}\Omega^2(x_1^2 + x_2^2) - kx_1x_2 \quad (10)$$

with  $\Omega = \sqrt{\omega^2 + k}$ . By rotating the coordinate system to use  $y_1 = (x_1 + x_2)/\sqrt{2}$  and  $y_2 = (x_1 - x_2)/\sqrt{2}$  this becomes

$$V_{\text{eff}}(y_1, y_2) = \frac{1}{2}\omega^2 y_1^2 + \frac{1}{2}(\omega^2 + 2k)y_2^2 \quad (11)$$

Thus this coupling gives an additional restoring force acting on the difference in position of the two oscillators, which will tend to keep their positions correlated. Larger values of  $k$  give stronger correlations, but also require more control force.

In summary, these examples illustrate a variety of control methods that can be applied. Although for simplicity we have considered harmonic oscillations, the control computations could also allow  $k$  to vary with  $x$ , e.g., so the control is smaller when the system is near the desired position. This amounts to adding aharmonicity to the system. Even more generally,  $k$  could also be time-dependent: instead of the time-dependent force acting uniformly on the system as treated above, this would allow more complex control forces. Although more difficult to analyze, this flexibility greatly extends the options for control strategies.

Therefore, one way to design quantum control methods is to apply standard classical control algorithms, with some modification, directly to quantum systems. One major difference arises from the fact that employing quantum computers requires the use of reversible control programs, and as a result there is no possibility of creating dissipative (non-conservative) control laws. An, example, described above is trying to control to the desired location of the center of the packet by applying force to all  $x$  values. Although conceptually simple, it is by no means obvious that a control designed under the assumption of zero packet width (i.e., a classical algorithm) will continue to work for quantum systems. Moreover, some behaviors, such as the width of the packet, have no classical analogs so to control those aspects of the system will require uniquely quantum mechanical control algorithms. Furthermore, control algorithms could also make use of interference. An example would be combining several different classical control algorithms so as to cancel out an undesired behavior, even though each control by itself produces that behavior. This gives additional options for control algorithms, beyond attempting to use a single classical method. As another example, the control could also manipulate the phase of the wave packet. A superposition of such controls, e.g., based on different models of the system, may be possible where the phase varies slowly near the correct model, thus giving a strong contribution to the final result from the control choice in the superposition that actually matches the system parameters.

## 5 Applications

An important practical issue involves the construction of the devices required for quantum smart matter. While some progress has been reported on the basic components of quantum computers [3, 15, 48], quantum smart matter also requires sensing and actuation abilities that can be coupled to such computations. Thus progress in the development of quantum based sensing and actuation is needed before applications, such as those presented in this paper, become possible. In addition, it is also important to understand the relative time scales possible for quantum computing and various physical behaviors that might be controlled. This knowledge is required to develop effective sensing and actuation mechanisms for any particular application. Only when the computing is relatively fast can we hope to construct smart matter for the behavior in question.

To illustrate the concept of quantum smart matter, we present several potential applications. These examples are based on applying microscopic, decentralized or local, control to create a desired macroscopic result. These applications are active camouflage; custom manipulated material properties; control of certain chemical reaction rates; and nonlinear, active springs for quantum machines. The key idea is to operate on the full quantum state through the control program to produce a desired (global) behavior. To some extent, classical controllers in smart matter could also be used. However, as described above

quantum computers allow for manipulating a wider range of behaviors, and in particular to apply feedback without disrupting the wave function.

## 5.1 Active Camouflage

Active camouflage takes advantage of the ability to create asymmetric, optical potentials within materials [44]. Manipulating these potentials allows the controller to manipulate the optical response to light striking that material and, thus, for example, change the color with which it appears to an external observer. This would allow quantum smart matter to determine the color of its exterior surroundings, and modify the material potentials to reflect a matching color. The end result is a material capable of actively blending in with its surroundings like a chameleon.

There are several different time scales involved in this example. First is the fast interaction of light with the material. This is likely to be much faster than the time scale governing computational speed. However, for this application, the relevant physical time scale is the rate at which environment conditions change, which is much slower. Hence substantial time could be available for computation, perhaps using feedback to gradually adjust the potentials to achieve a desired result.

## 5.2 Active Materials

Active materials employ quantum smart matter to manipulate their lattice structure to customize their mechanical properties. This could also be used to locally adjust the propagation of phonons or the specific heat of the material, as well as to actively adjust the material's mechanical behavior. These abilities would enable the development of active thermal and acoustic isolators. In addition, such behaviors could be employed to manipulate the displacement of a structure under specific disturbance inputs, or to direct the thermal stresses in a material to a desired location, similar to the way in which a photocopier directs paper along a specific path.

Several applications could be accomplished using classical computers for control. For example, a signal might be sent to a portion of the material to change the state of its control on the lattice structure, modifying the stiffness, ductility, and strength of the material as a result. Such control inputs create a material that (at different times) is both stiff and flexible, depending on what properties were required, and where they were required. One important application of such a material is the forming of high strength alloys. In this instance, a high strength alloy could actively be made more ductile for forming, and then actively re-strengthened once in the proper shape. Such an approach provides an elegant solution for the typical difficulty encountered in industrially forming high strength materials such as titanium.

Similar to the previous example, the relative time scales of physical interaction and computational action are important. In this case, the physical interaction occurs only as fast as the actuator bandwidth, while the computational bandwidth is a function of the quantum computers. The relevant time scale in this example is the desired speed for adjusting the material properties. However, these applications involve mechanical changes, which typically operate slowly compared to computational speeds.

## 5.3 Adjusting Reaction Rates

Chemical reaction rates can be affected by the local environment, such as electric fields due to nearby ions. Smart matter capable of adjusting fields could be used to modify reaction rates at a surface. Alternatively, the material could be dispersed throughout solutions containing the reactants. Coordinated programs running on the individual pieces could then adjust reaction rates in a bulk medium. This example illustrates that smart matter need not consist of a single connected material since any necessary communication among the controllers could use light or acoustic waves rather than wires. A more subtle

control would use local electric fields generated by the active devices in a distributed version of controlling reactions through external fields, a method that can also exploit quantum interference [16, 51]. Chemical reactions can also be controlled through mechanical forces [22, 26], thus providing another path for smart matter to influence chemical behaviors. One possible application would be the control of certain enzyme reactions. More generally, this would amount to a programmable catalyst.

Since reaction rates are generally quite rapid, this application would not involve active feedback response during reactions. Rather the control would take place by modifying the conditions for the reactions at a slower time scale, leading to changes in the overall reaction rate or the mix of products. This could be done both through the reduction of critical reaction elements and by using external field changes previously determined to be useful. Feedback at this slower time scale would still be useful for controlling complex reactions for which accurate models are difficult to evaluate.

## 5.4 Programmable Springs

Controlled nonlinear springs could be created by using quantum smart matter to control the bond strength between two (or several) molecules. This control could also be used as a finer scale version of current methods that modify molecular motion [16]. Specifically, electric fields could be generated to control the bond strength between two molecules, creating an active spring which might be utilized in quantum machines.

The relevant time scale in this case is dependent on the application of the active spring created. Specifically, any application of such a spring will have a maximum bandwidth that is necessary. As in the active material example, this will involve mechanical time scales, leaving plenty of time for computation.

## 6 Conclusions

We have described an application of quantum computers to control the behavior of materials. Even fairly small computers, involving only a few bits, may be able to produce useful new behaviors that would otherwise be difficult to fabricate directly. The use of such programmable materials could allow for experiments on the behavior of many possible structures before deciding which few to actually attempt to fabricate. In this way, quantum smart matter could be used as a simulator for different quantum structures [38]. It could also serve as an experimental platform for examining a range of macroscopic quantum effects by introducing programmable correlations in the overall quantum state of the material.

However, quantum computers face serious implementation difficulties of decoherence and error control [36], especially for programs that require many steps. While substantial difficulties remain before such devices can be constructed, there is encouraging progress in the development of the basic components needed for quantum computation [3, 15, 48] and methods for error control [46]. The simple individual programs useful for smart matter may be less susceptible than others proposed for difficult computational problems, but on the other hand any requirement for communication over large distances will increase the difficulty of avoiding undesired coupling to the environment. This provides another reason to favor local, distributed control methods over the use of global controls. Some local communications among the devices may provide an application for proposals to transmit quantum states [6].

We have suggested some possible applications of such capabilities, but it remains to be seen whether the capacity to operate on superpositions provides enough of an improvement over classical computers to justify the difficulty in maintaining coherence. Finally, if the promise of quantum computing is realized to improve combinatorial search, e.g., for factoring [47, 14] or more general cases [12, 30, 28], this capability could also be used to give very complex potentials for the behavior of matter.

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